

Hadronic Parity Violation

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Fermilab, SubZ⁰ Workshop

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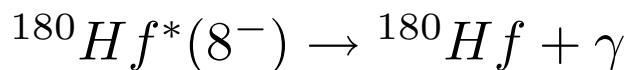
Problem:

Parity violating effects in strong

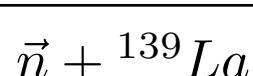
and electromagnetic hadronic interactions.

Examples:

First experiment—PV in pp by Tanner (1957)



$$A_\gamma = -(1.66 \pm 0.18) \times 10^{-2} \quad \text{PRC4, 1906 (1971)}$$



$$A_z = (9.55 \pm 0.35) \times 10^{-2} \quad \text{PRC44, 2187 (1991)}$$

Theoretical Clues

Seminal paper: "Parity Nonconservation in Nuclei",
F. Curtis Michel PR133B, 329 (1964)

1964 → 2003

Great Progress in Particle/Nuclear Physics

Standard Model

BUT remain great unsolved problems at low energy:

- i) $\Delta I = \frac{1}{2}$ Rule
- ii) CP Violation
- iii) Hypernuclear Weak Decay
- iv) Hadronic Parity Violation

All deal with $J_\mu^{\text{hadron}} \times J_\mu^\mu$

Theoretical Picture

$$\mathcal{H}_w = \frac{G_F}{\sqrt{2}} J_\mu^\dagger J^\mu$$

with

$$J_\mu = J_\mu^{\text{hadron}} + J_\mu^{\text{lepton}}$$

Then

- i) $J_\mu^{\text{lepton}} \times J_\mu^{\text{lepton}} \longrightarrow \mu^- \rightarrow e^- + \bar{\nu}_e + \nu_\mu$
- ii) $J_\mu^{\text{lepton}} \times J_{\text{hadron}}^{\mu\dagger} \longrightarrow n \rightarrow p + e^- + \bar{\nu}_e$
- iii) $J_\mu^{\text{hadron}} \times J_{\text{hadron}}^{\mu\dagger} \longrightarrow \text{hadronic PV}$

Canonical size: $\mathcal{H}_w / \mathcal{H}_{\text{str}} \sim G_F m_\pi^2 \sim 10^{-7}$

Isolate via PV effects in strong and/or EM processes

Standard Model Picture

$$\mathcal{H}_w = \frac{G_F}{\sqrt{2}}(J_c^\dagger \times J_c + \frac{1}{2}J_n^\dagger \times J_n)$$

with

$$J_\mu^c = \bar{u}\gamma_\mu(1 + \gamma_5)(\cos\theta_c d + \sin\theta_c s)$$

$$J_\mu^n = \bar{u}\gamma_\mu(1 + \gamma_5)u - \bar{d}\gamma_\mu(1 + \gamma_5)d - \bar{s}\gamma_\mu(1 + \gamma_5)s$$

$$-4\sin^2\theta_w J_\mu^{em}$$

Then

$\mathcal{H}_w(\Delta S = 0)$ carries $\Delta I = 0, 1, 2$

leads to

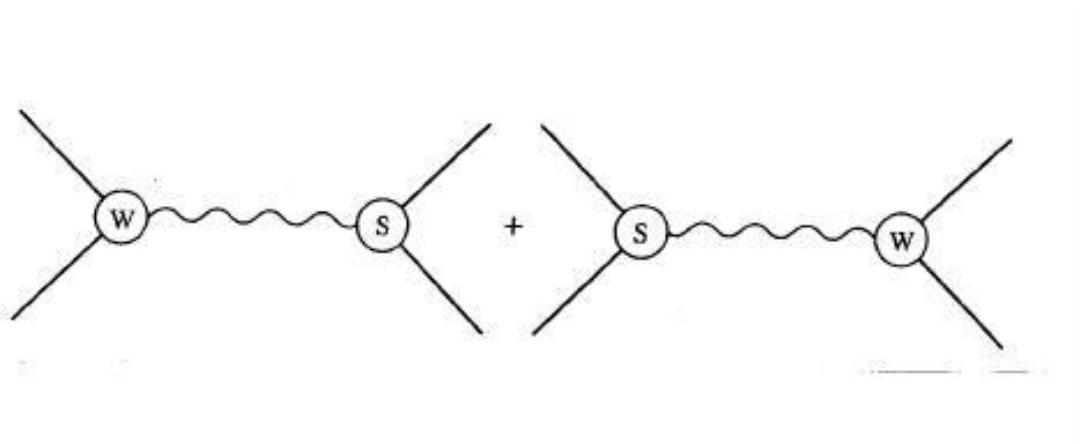
1980: DDH Approach

Meson exchange gives good picture of PC NN interaction, with

$$\mathcal{H}_{\text{st}} = ig_{\pi NN} \bar{N} \gamma_5 \tau \cdot \pi N + g_\rho \bar{N} \left(\gamma_\mu + i \frac{\mu_V}{2M} \sigma_{\mu\nu} k^\nu \right) \tau \cdot \rho^\mu N$$

$$+ g_\omega \bar{N} \left(\gamma_\mu + i \frac{\mu_S}{2M} \sigma_{\mu\nu} k^\nu \right) \omega^\mu N$$

so use for PV NN



Then need PV weak couplings:

$$\mathcal{H}_{\text{wk}} = \frac{h_\pi}{\sqrt{2}} \bar{N} (\tau \times \pi)_3 N$$

$$+ \bar{N} \left(h_\rho^0 \tau \cdot \rho^\mu + h_\rho^1 \rho_3^\mu + \frac{h_\rho^2}{2\sqrt{6}} (3\tau_3 \rho_3^\mu - \tau \cdot \rho^\mu) \right) \gamma_\mu \gamma_5 N$$

$$+\bar{N}(h_\omega^0\omega^\mu+h_\omega^1\tau_3\omega^\mu)\gamma_\mu\gamma_5N-h_\rho^{'1}\bar{N}(\tau\times\rho^\mu)_3\frac{\sigma_{\mu\nu}k^\nu}{2M}\gamma_5N$$

Gives two-body PV NN potential

$$\begin{aligned} V^{\text{PNC}} = & i \frac{f_\pi g_{\pi NN}}{\sqrt{2}} \left(\frac{\tau_1 \times \tau_2}{2} \right)_3 (\sigma_1 + \sigma_2) \cdot \left[\frac{\mathbf{p}_1 - \mathbf{p}_2}{2M}, f_\pi(r) \right] \\ & -g_\rho \left(h_\rho^0 \tau_1 \cdot \tau_2 + h_\rho^1 \left(\frac{\tau_1 + \tau_2}{2} \right)_3 + h_\rho^2 \frac{(3\tau_1^3\tau_2^3 - \tau_1 \cdot \tau_2)}{2\sqrt{6}} \right) \\ & \times ((\sigma_1 - \sigma_2) \cdot \left\{ \frac{\mathbf{p}_1 - \mathbf{p}_2}{2M}, f_\rho(r) \right\}) \\ & + i(1 + \chi_V) \sigma_1 \times \sigma_2 \cdot \left[\frac{\mathbf{p}_1 - \mathbf{p}_2}{2M}, f_\rho(r) \right] \\ & -g_\omega \left(h_\omega^0 + h_\omega^1 \left(\frac{\tau_1 + \tau_2}{2} \right)_3 \right) \\ & \times ((\sigma_1 - \sigma_2) \cdot \left\{ \frac{\mathbf{p}_1 - \mathbf{p}_2}{2M}, f_\omega(r) \right\}) \\ & + i(1 + \chi_S) \sigma_1 \times \sigma_2 \cdot \left[\frac{\mathbf{p}_1 - \mathbf{p}_2}{2M}, f_\omega(r) \right] \end{aligned}$$

$$-(g_\omega h_\omega^1 - g_\rho h_\rho^1) \left(\frac{\tau_1 - \tau_2}{2} \right)_3 (\sigma_1 + \sigma_2) \cdot \left\{ \frac{\mathbf{p}_1 - \mathbf{p}_2}{2M}, f_\rho(r) \right\}$$

$$-g_\rho h_\rho^{1'} i \left(\frac{\tau_1 \times \tau_2}{2} \right)_3 (\sigma_1 + \sigma_2) \cdot \left[\frac{\mathbf{p}_1 - \mathbf{p}_2}{2M}, f_\rho(r) \right]$$

where

$$f_V(r) = \exp(-m_V r) / 4\pi r$$

Problem is to calculate seven weak couplings

Historical Approaches

Theoretical

1964: Michel—Factorization

$$\langle \rho^+ n | \mathcal{H}_{\text{wk}}^c | p \rangle = \frac{G}{\sqrt{2}} \cos^2 \theta_c \langle \rho^+ n | V_+^\mu A_\mu^- | p \rangle$$

$$\approx \frac{G}{\sqrt{2}} \cos^2 \theta_c \langle \rho^+ | V_+^\mu | 0 \rangle \langle n | A_\mu^- | p \rangle$$

1968: Tadic, Fischbach, McKeller— $SU(3)$ Sum Rule

$$\langle \pi^+ n | \mathcal{H}_{\text{wk}}^c | p \rangle = -\sqrt{\frac{2}{3}} \tan \theta_c (2 \langle \pi^- p | \mathcal{H}_{\text{wk}} | \Lambda^0 \rangle$$

$$- \langle \pi^- \Lambda^0 | \mathcal{H}_{\text{wk}} | \Xi^- \rangle)$$

1980: DDH—Quark Model plus Symmetry

Represent states by

$$|N\rangle \sim b_{qs}^\dagger b_{q's'}^\dagger b_{q''s''}^\dagger |0\rangle$$

$$|M\rangle \sim b_{qs}^\dagger d_{q's'}^\dagger |0\rangle$$

and

$$\mathcal{H}_{\text{wk}} \sim \frac{G}{\sqrt{2}} \bar{\psi} \mathcal{O} \psi \bar{\psi} \mathcal{O}' \psi$$

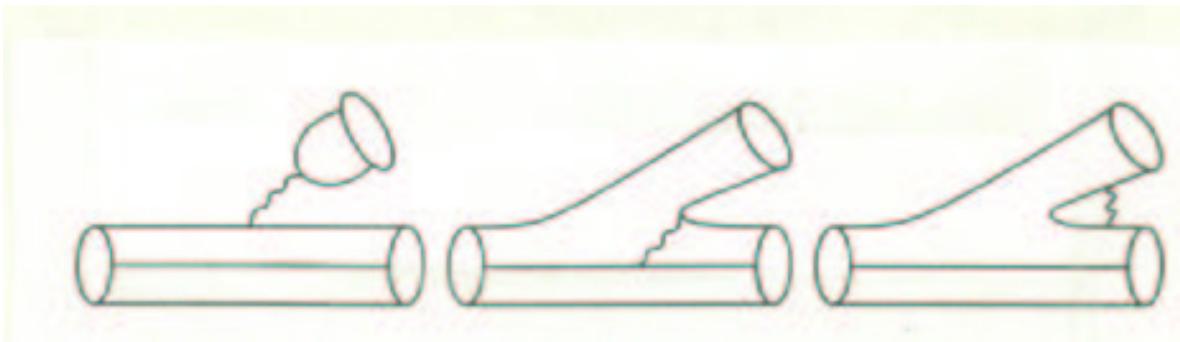
Then structure of weak matrix element is

$$\begin{aligned} < M N | \mathcal{H}_{\text{wk}} | N > &= \frac{G}{\sqrt{2}} < 0 | (b_{qs} b_{q's'} b_{q''s''}) (b_{qs} d_{q's'}) \\ &\times \bar{\psi} \mathcal{O} \psi \bar{\psi} \mathcal{O}' \psi (b_{qs}^\dagger b_{q's'}^\dagger b_{q''s''}^\dagger) | 0 > \times R \end{aligned}$$

with R a complicated radial integral—*i.e.*, a "Wigner-Eckart" theorem

$$\langle MN|\mathcal{H}_{\text{wk}}|N \rangle \sim \text{known "geometrical" factor} \times R$$

Find three basic structures



Here first is factorization, but two additional diagrams

Represent in terms of "Reasonable Range" and "Best Value"

Coupling	DDH Reasonable Range	DDH “Best” Value
h_π	$0 \rightarrow 30$	12
h_ρ^0	$30 \rightarrow -81$	-30
h_ρ^1	$-1 \rightarrow 0$	-0.5
h_ρ^2	$-20 \rightarrow -29$	-25
h_ω^0	$15 \rightarrow -27$	-5
h_ω^1	$-5 \rightarrow -2$	-3

all times sum rule value 3.8×10^{-8}

Experimental

Can use nucleus as amplifier—first order perturbation theory

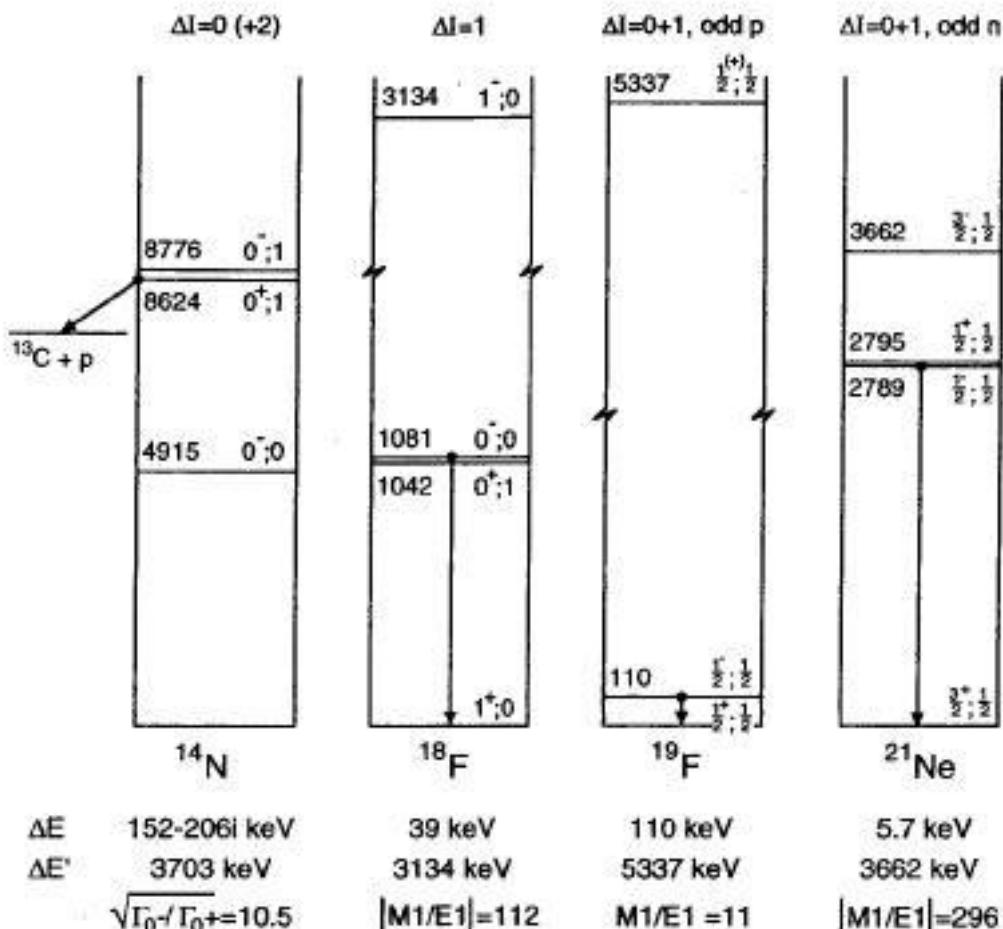
$$|\psi_{J+}\rangle \simeq |\phi_{J+}\rangle + \frac{|\phi_{J-}\rangle \langle \phi_{J-}| \mathcal{H}_{\text{wk}} | \phi_{J+}\rangle}{E_+ - E_-}$$

$$= |\phi_{J+}\rangle + \epsilon |\phi_{J-}\rangle$$

$$|\psi_{J-}\rangle \simeq |\phi_{J-}\rangle + \frac{|\phi_{J+}\rangle \langle \phi_{J+}| \mathcal{H}_{\text{wk}} | \phi_{J-}\rangle}{E_- - E_+}$$

$$= |\phi_{J-}\rangle - \epsilon |\phi_{J+}\rangle$$

Then enhancement if $\Delta E \ll$ typical spacing.
Examples are



Typical results: Circular polarization in ^{18}F E1 decay of 0^- 1.081 MeV excited state

$$|P_\gamma(1081)| = \begin{cases} (-7 \pm 20) \times 10^{-4} & \text{Caltech/Seattle} \\ (3 \pm 6) \times 10^{-4} & \text{Florence} \\ (-10 \pm 18) \times 10^{-4} & \text{Mainz} \\ (2 \pm 6) \times 10^{-4} & \text{Queens} \\ (-4 \pm 30) \times 10^{-4} & \text{Florence} \end{cases}$$

Asymmetry in decay of polarized $\frac{1}{2}^-$ 110 KeV excited state of ^{19}F

$$A_\gamma = \begin{cases} (-8.5 \pm 2.6) \times 10^{-5} & \text{Seattle} \\ (-6.8 \pm 1.8) \times 10^{-5} & \text{Mainz} \end{cases}$$

Circular Polarization in ^{21}Ne E1 decay of $\frac{1}{2}^-$ 2.789 Mev excited state

$$P_\gamma = \begin{cases} (24 \pm 24) \times 10^{-4} & \text{Seattle/Chalk River} \\ (3 \pm 16) \times 10^{-4} & \text{Chalk River/Seattle} \end{cases}$$

Also results on NN systems which are not enhanced:

$$\text{pp: PSI } A_z^{tot}(45.0 \text{ MeV}) = -(1.57 \pm 0.23) \times 10^{-7}$$

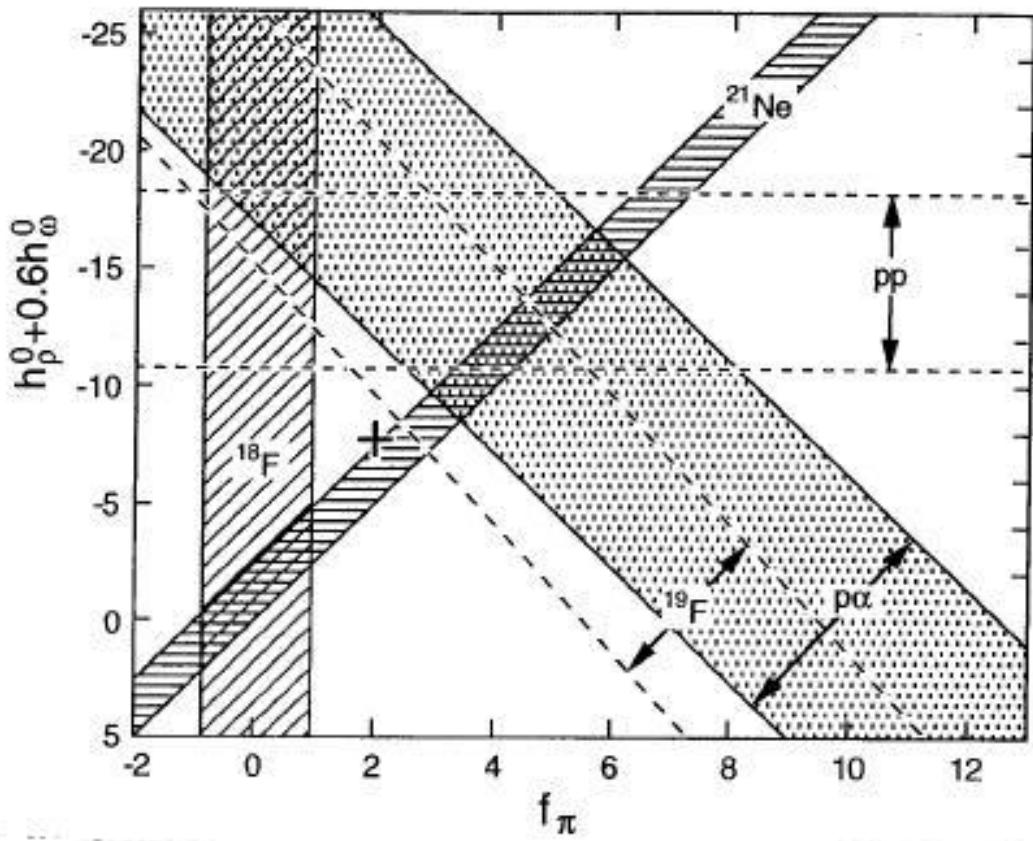
$$\text{pp: Bonn } A_z(13.6 \text{ MeV}) = -(0.93 \pm 0.20 \pm 0.05) \times 10^{-7}$$

$$\text{p}\alpha: \text{PSI } A_z(46.0 \text{ MeV}) = -(3.3 \pm 0.9) \times 10^{-7}$$

Summary of present results in nuclei:

Reaction	Excited State	Measured Quantity	Experiment ($\times 10^{-5}$)	Theory ($\times 10^{-5}$)
$^{13}\text{C}(\text{p}, \alpha)^{14}\text{N}$	$J=0^+, T=1$ 8.264 MeV $J=0^-, T=1$ 8.802 MeV	$[A_z(35^\circ) - A_z(155^\circ)]$	0.9 ± 0.6	-2.8
$^{19}\text{F}(\text{p}, \alpha)^{20}\text{Ne}$	$J=1^+, T=1$ 13.482 MeV $J=1^-, T=0$ 13.462 MeV	$A_z(90^\circ)$ A_z A_x	150 ± 76 660 ± 240 100 ± 100	
^{18}F	$J=0^-, T=0$ 1.081 MeV	P_γ mean	-70 ± 200 -40 ± 300 -100 ± 180 17 ± 58 27 ± 57 12 ± 38	208 ± 49
^{19}F	$J=\frac{1}{2}^-, T + \frac{1}{2}$ 0.110 MeV	A_γ mean	-8.5 ± 2.6 -6.8 ± 2.1 -7.4 ± 1.9	-8.9 ± 1.6
^{21}Ne	$J=\frac{1}{2}^-, T = \frac{1}{2}$ 2.789 MeV	P_γ	80 ± 140	46

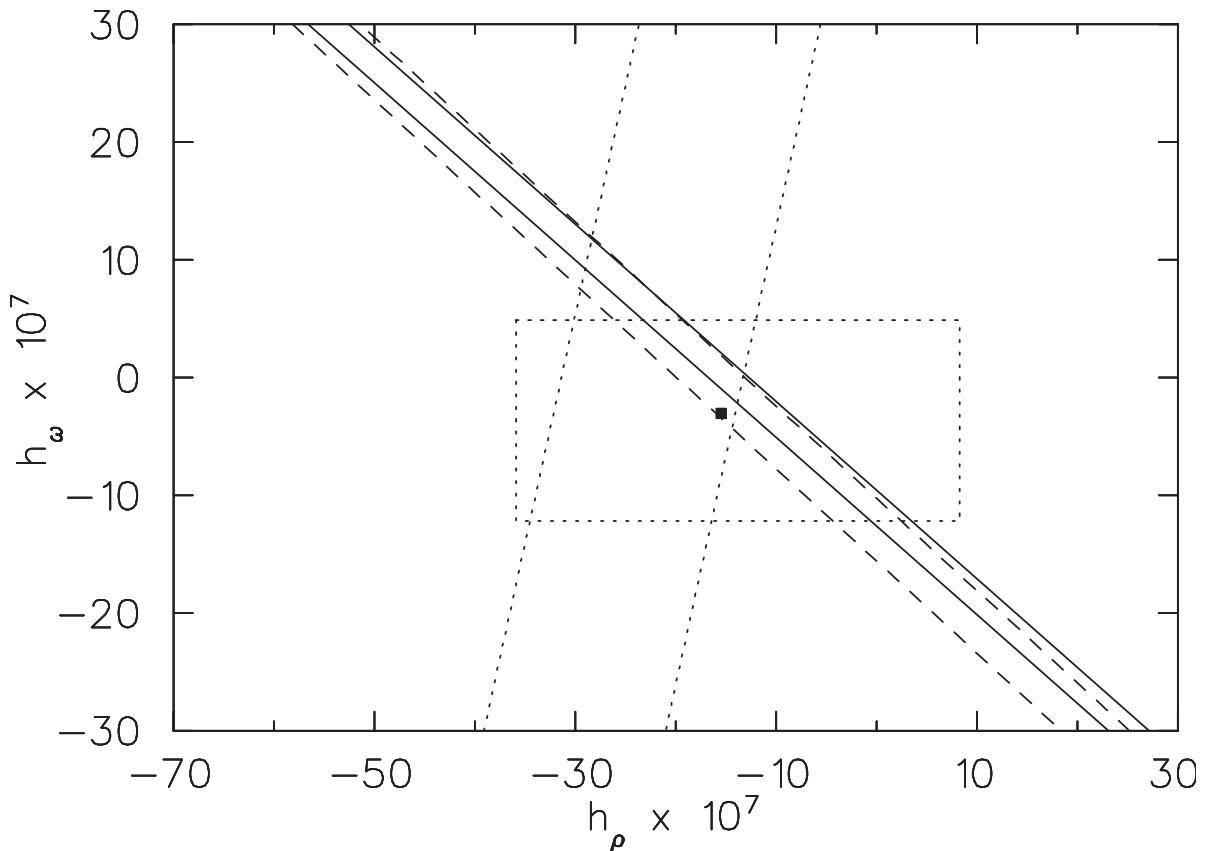
Graphical Summary



TRIUMF E497

$\vec{p}p$ scattering at 221 MeV—special energy S-P vanishes—sensitive to P-D mixing

$$A_L = (0.84 \pm 0.29 \pm 0.27) \times 10^{-7}$$



Now What?

A Plan

Note low energy NN PV characterized by five amplitudes:

- i) $d_t(k)$ — 3S_1 — 1P_1 mixing: $\Delta I = 0$
- ii) $c_t(k)$ — 3S_1 — 3P_1 mixing: $\Delta I = 1$
- iii) $d_s^{0,1,2}(k)$ — 1S_0 — 3P_0 mixing: $\Delta I = 0, 1, 2$

Unitarity requires

$$d_{s,t}(k) = |d_{s,t}(k)| \exp i(\delta_S(k) + \delta_P(k))$$

Danilov suggests

$$d_i(k) \approx \lambda_i m_i(k)$$

so

$$\lim_{k \rightarrow 0} c_t(k), d_t(k), d_s^{0,1,2}(k) = \rho_t a_t, \lambda_t a_t, \lambda_s^{0,1,2} a_s$$

Need five independent experiments—use nuclei with $A \leq 4$. Interpret using Desplanques and Missimer

i) $\vec{p}p$ scattering

$$pp(13.6\text{MeV}) \quad A_L = -0.48M\lambda_s^{pp}$$

$$pp(45\text{MeV}) \quad A_L = -0.82M\lambda_s^{pp}$$

ii) $\vec{p}\alpha$ scattering

$$p\alpha(46\text{MeV}) \quad A_L = -M[0.48(\lambda_s^{pp} + \frac{1}{2}\lambda_s^{pn}) + 1.07(\frac{1}{2}\lambda_t + \rho_t)]$$

iii) Radiative Capture— $np \rightarrow d\gamma$

a) Circular Polarization : $P_\gamma = M(0.63\lambda_t - 0.16\lambda_s^{np})$

b) Photon asymmetry : $A_\gamma = -0.11M\rho_t$

iv) Neutron spin rotation in He

$$\frac{d\phi^{n\alpha}}{dz} = [0.85(\lambda_s^{nn} - \frac{1}{2}\lambda_s^{pn}) - 1.89(\rho_t - \frac{1}{2}\lambda_t)]m_N \text{ rad/m}$$

Status of experiments

- a) pp(13.6 MeV) performed at Bonn
- b) pp(45 MeV) performed at PSI
- c) p α (46 MeV) performed at PSI
- d) $P_\gamma(np)$ Athens, Duke, ???
- e) $A_\gamma(np)$ scheduled at Lansce
- f) $\phi^{n\alpha}$ scheduled at NIST

What's needed?

- i) Precision Experiments
 - a) Bowman et al.—LANSCE
 - b) Snow et al.—NIST
 - c) Weller ?, Papanicolas ?
- ii) State of the art NN theory:
Carlson, Wiringa, Gibson, etc.
- iii) Effective field theory
BH, Ramsey-Musolf, van Kolck, etc.

Result is understanding of PVNN by 2007

Predicting the Future

After reliable set of couplings obtained

- a) Confirm via other experiments in $A < 4$ systems
- b) Use these to analyze previous results in heavier nuclei
- c) Confront measured numbers with fundamental theory via lattice and/or other methods
- d) Reliably predict effects in other experiments